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Development of a model for single-sided, wind-driven natural ventilation in buildings

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Abstract:

Natural ventilation is a simple and energy-efficient method to adjust the indoor environment. This study aims to develop a model for predicting the total flow rate of single-sided natural ventilation. It is motivated by the fact that the wind-driven ventilation itself is commonly considered to consist two components – a mean component and a fluctuating component. Pulsating flow rate, mean and broadband ventilation rate are discussed and considered in the model due to fluctuating wind velocity driven by the fluctuating pressures and unsteady flows around the opening. The new model shows that the total flow rate is majorly caused by pulsating flow when the area of opening is small, but it is mainly caused by mean flow in the case of large opening. Opening ratio can be taken as a boundary to distinguish the small opening area and the larger one from the case analyses in this study. Reynolds Averaged Navier-Stoke model, large eddy simulation, and other correlations are utilized to validate the developed model. The results of current method agree reasonably well with those of transient simulation. Finally, a simplified version of the model is developed which is useful for predicting the total flow rate of natural ventilation in buildings. Practical application: The model can be applied to predict the total flow rate of single-sided natural ventilation in buildings due to wind pressure. The model shows that the total flow rate is majorly caused by the pulsating flow when the area of opening is small, but it is mainly caused by the mean flow in the case of large opening. An opening ratio of 3% can be taken as a boundary to distinguish the small opening area and the large one from the cases analysed in this study.

Keywords: flow rate, single-sided ventilation; wind-driven, natural ventilation, numerical simulation;

A	opening area , m^2	C_1、C_2、C_3	empirical coefficients depending on wind direction
B	building width , m		
$f(\beta_W)$, $\Delta C_{P,opening}$	function of wind direction	c_1	dimensionless coefficient depending on the wind effect
H	building height, m	c_2	buoyancy constant

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Nomenclature

h	opening height, m	c_3	turbulence constant
L	building length, m	C_d	discharge coefficient
l	opening width, m	C_p	wind pressure coefficient
m	shape parameter	Q	total flow rate, m^3/s
$p(\bar{U})$	probability density of mean wind velocity	Q_B	mean plus broad banded ventilation rate , m^3/s
T	time, s	$Q_{ins,T}$	flow rate calculated by integration method and transient simulation, m^3/s
U	wind velocity, m/s		
U_{10}	wind velocity at height 10m, m/s	Q_{mean}	flow rate calculated by integration method and steady-state simulation, m^3/s
U_{max}	maximum wind velocity, m/s		
$U_{m,n}$	wind velocity of cell in flow field, m/s	Q_p	pulsating flow rate, m^3/s
$\bar{U}$	mean velocity, m/s	$\bar{Q}$	mean flow rate , m^3/s
u^*	the atmospheric boundary layer friction velocity, m/s		
V_R	mean wind velocity at reference height, m/s		
z_0	height of neutral plane, m	*Greek symbols*	
z_{r0}	the roughness parameter, m	ΔT	temperature difference, K
z_{ref}	reference height, m	σ	RMS value
c	scale parameter	κ	the Karman constant

1 Introduction

Natural ventilation is a simple method to improve indoor thermal comfort, maintain acceptable indoor air quality, and reduce energy consumption. Different types of natural ventilation strategies exist: single-sided ventilation, cross-flow ventilation and stack ventilation [1]. The cross ventilation is often favored for its larger air exchange rate than the single-sided ventilation. However, in most cases only few buildings can achieve cross-ventilation due to the interior partitions, obstacles, and thicknesses. Therefore, single-sided ventilation is still of great importance in building design [2].

The wind-driven natural ventilation through a building consists of two components - a mean component driven by the mean pressure field at the ventilation openings, and a fluctuating component driven by the fluctuating pressures and unsteady flows around the openings [3]. Techniques to predict the fluctuating air infiltration have earlier been investigated and developed. The latest review about it was carried out by Fariborz Haghighat[4] in 2000. He summarized models to different group: Pulsation [5], Mechanical-system simulation [6], Correlation [7-9], Numerical simulation [10], Resonator [11] and Power spectrum analysis [12]. At the same year, D.W. Etheridge[13,14] studied the effects of unsteady wind pressures on the mean flow rates and the instantaneous flow rates in certain types of purposed-designed naturally ventilated buildings, and derived a procedure for calculating the mean flow rates when the unsteady effects are large. Wang and Chen [2] presented a new empirical model for predicting single-sided, wind-driven natural ventilation in buildings.

H.K. Malinowski pointed out that the fluctuating component of ventilation can be considered to consist of a number of distinct phenomena [15]. The first mechanism is broad banded ventilation, the second is pulsating flow, and the third is known as eddy penetration, or shear layer ventilation. Mp Straw [3] analyzed the relative magnitudes of the ventilation produced by the various fluctuating flow mechanisms (broad banded, resonant and shear layer) and discussed the methods of calculating the total ventilation rate from the mean and the fluctuating components.

The objective of the current study is to analyze and discuss how to get total flow rate of single-sided, wind-driven natural ventilation in buildings. The first section of this paper discussed the model of pulsating flow rate, which is followed by the possible method of calculating total flow rate. Finally, CFD studies and other models were utilized to verify the method.

2 Model development

The fluctuating flow is totally caused by three mechanisms: broad banded ventilation, pulsating flow and eddy penetration. Therefore, the model developed in this investigation consists of four parts:

(1) mean flow rate, (2) Broad banded flow rate, (3) pulsating flow rate, and (4) eddy penetration flow rate.

2.1 Pulsating flow

Many researchers [3,5,12] pointed out that pulsating flow caused by a body of fluid being driven perpendicular to the opening by the difference between the external and internal pressures, and it are significantly affected by the geometry of the enclosure and by air compressibility. However, Wang and Chen [2] didn’t consider this flow mechanism. The governing equation in their studies was based on the non-uniform pressure distribution along the opening height. The fluctuating ventilation rate contributed by pulsating flow in their model only has relation with root mean square of fluctuating velocity, opening height and opening width. They just derived the correlation of pulsating flow rate from expression of the mean flow rate directly.

In our early study [16], a simple model (hereafter Hu’s model) was proposed which can predict the pulsating flow rate of single-sided ventilation when wind direction is perpendicular to opening. When reference mean velocity, roughness parameter, area of opening and volume of room were given, the pulsating flow rate could be calculated out easily. That study also demonstrated that the ventilation rate of pulsating flow is inextricably bound up with some factors, for example, area of opening, volume of room, mean wind velocity and turbulence intensity. Here one case published by Haghighat [12] was calculated again by Hu’s model. The results were listed in Table1.

Table 1 Case comparison of pulsating flow rate

Main Parameters			Haghighat’s model (m^3/s)	Hu’s model (m^3/s)
Volume	Opening area	Mean wind velocity		
1000	0.05	10	0.0606	0.0521

Two results have the same order of magnitude, and the relative error between them is about 14%. Besides, similar expressions about effect of opening area and room volume on pulsating flow rate as Haghighat’s study were obtained [16]. In the later content of the paper, the results of pulsating flow rate would be verified by CFD results to a certain degree.

2.2 Mean and broad banded ventilation

The mean flow is driven by the mean pressure field at the ventilation openings. Wang and Chen’s expression [2] was adopted here.

$$\bar{Q} = \frac{C_d l \sqrt{C_p} \int_{z_0}^{h} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{1/7}} \bar{U} \tag{1}$$

where $\bar{Q}$ is the mean flow rate, C_d is the discharge coefficient, $C_p$is the pressure coefficient, l is the opening width, $z_0$is the position of the neutral plane in the direction of z, and z_{ref} is reference height that is taken here to be 10m. $\bar{U}$ is reference mean velocity.

Considering the fluctuation of wind velocity and the time-distance of 10 minutes, the mean wind velocity also varies with time. Then, mean wind velocity can be described by the mean value $\bar{U}$, and standard deviation $\sigma_{\bar{U}}$. As Straw [3] pointed out, broad banded ventilation represents surface pressure fluctuations at the opening across a wide range of frequencies, and it can effectively be regarded as a modification of the mean ventilation mechanism. For this reason, the broad banded ventilation, σ_Q, can be calculated by

$$\sigma_Q = \frac{C_d l \sqrt{C_p} \int_{z_0}^{h} \sqrt{z^{2/7} - z_0^{2/7}}\, dz}{z_{ref}^{1/7}} \sigma_{\bar{U}} \tag{2}$$

Therefore, the mean plus broad banded ventilation, Q_B, can be calculated from [3]

$$Q_B = \bar{Q} + \left(\frac{2\sqrt{2}}{\pi}\right) \sigma_Q \sqrt{1 - \frac{1}{2}(\frac{\bar{Q}}{\sigma_Q})^2} \tag{3}$$

Equation applies only for ($\bar{U}/\sigma_{\bar{U}} < \sqrt{2}$). Above this value, the total ventialiton is equal to the mean ventilation.

2.4 Eddy penetration flow

Wang and Chen studied the effect of eddy penetration in the frequency domain based on fast Fourier transform [2]. Chu also proposed different methods for calculating the fluctuating ventilation rate due to eddy penetration [17]. Wang and Chen [2] found that the eddy penetration was zero, and the penetration was low when the angle was around 70^{o}. Therefore, the flow rate due to eddy penetration was ignored here because that wind direction was assumed to be perpendicular to the opening in this study.

2.5 Total flow rate

The total flow rate is majorly caused by pulsating flow when the opening area is small in single-sided natural ventilation. It could be assumed that the wind direction at the opening remains the same over a very short time in that condition.

$$Q_p = \sigma_{Qp} \frac{\sqrt{2}}{\pi} \tag{4}$$

σ_{Qp} can be calculated out by Hu's model [16].

When the opening area is large, the main driving force is pressure difference between upper zone and lower zone of the opening. Then the method introduced by Straw [3] also could be utilized here to calculate the total flow rate. The ventilation rate due to eddy penetration was ignored because that wind direction is perpendicular to the opening in this study, so following expressions could be wrote:

$$Q = \begin{cases} \bar{Q} & \text{when} \quad \bar{U}/\sigma_{\bar{U}} \geq \sqrt{2} \\ Q_B & \text{when} \quad \bar{U}/\sigma_{\bar{U}} < \sqrt{2} \end{cases} \tag{5}$$

3 Numerical simulation

Computational fluid dynamics (CFD) is a useful tool for the prediction of air movement in ventilated spaces [18]. It was usually utilized to investigate ventilation flows and focused on the mean flow properties [19, 20] and fluctuating characteristics of flow [21-26]. This section of the paper aimed to verify the above method of getting total flow rate.

There are two issues should be considered in numerical simulation of natural ventilation. The first one is turbulent models. Two models are regularly used: RANS（Reynolds Averaged Navier-Stoke）, and LES（Large Eddy Simulation）. RANS models provide effective time-average solutions. LES model provide more realistic results and it is superior to others in calculation of single-sided ventilation under the condition of unsteady wind pressure [26,27]. Ai [28] compared the predictive methods of flow rate in single-sided ventilation based on both the RANS and LES turbulence models. It was found that $\mathrm{ACH}_{\mathrm{RNG-mean}}$ (the RNG model plus integration method) and $\mathrm{ACH}_{\mathrm{LES-tracer}}$ (the LES model plus tracer gas decay method) values agree well with the measured data, $\mathrm{ACH}_{\mathrm{exp}}$. However, the inflow condition of no perturbations was utilized in his study. The second problem is the inflow turbulence boundary condition. The importance of defining proper inflow turbulence boundary condition while using LES was discussed by various researchers [29-33]. There are three types of inflow fluctuating algorithms, namely no perturbations, spectral synthesizer and vertex method in Fluent [34]. Spectral synthesizer is based on the random flow generation technique originally proposed by Kraichnan [35] and modified by Smirnov et al. [36]. In the following numerical simulation, the LES model and the fluctuating velocity algorithm of Spectral Synthesizer are used.

3.1 Computational domain and building model

The computational domain and building geometry were shown in Figure 1. The building dimension was L×B×H. The opening with dimension of l×h was in the center of upwind wall. The incident wind direction was perpendicular to the opening.

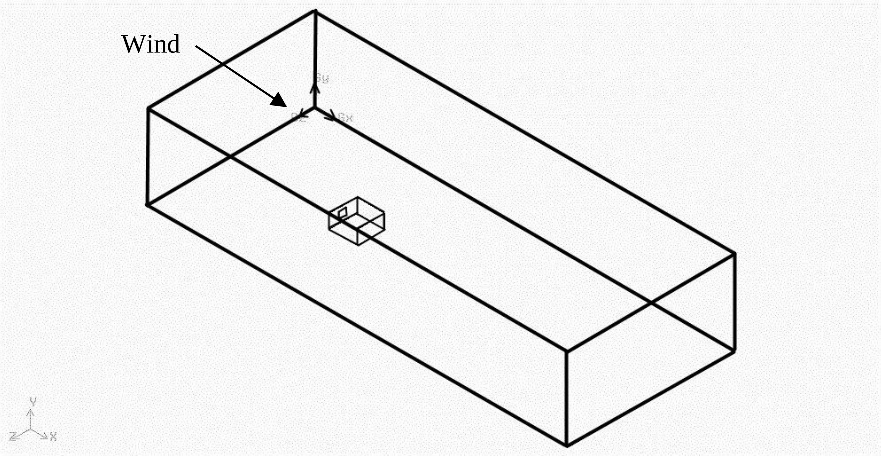


Figure 1 The computational zone and building model.

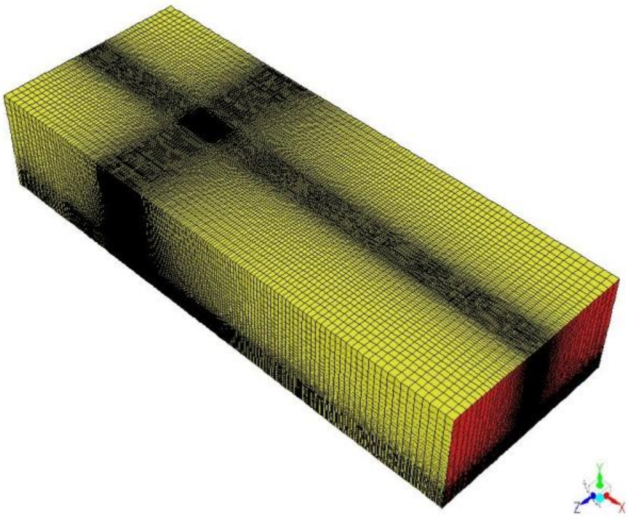


Figure 2 Computational grid of the zone.

Table 2 Five cases of simulation

Case	Building's dimension （L×B×H） (m×m×m)	Opening's dimension （l×h） (m×m)
1	6×4×3	0.5×0.5
2	6×4×3	0.5×1
3	8×6×3	1×1
4	8×8×4	1×1
5	8×8×4	2×2

Five different cases were listed in table1. Base on the guidelines [37], the lateral and the top boundary were set 5H away from the building, and the distance between the inlet boundary and the building was 8H and the outflow boundary was 20H behind the building. The blockage ratio of all cases were below 3% . Hexahedral structured gird was adopted as shown in Figure2. A number of grid refinements were made in opening area, and the building.

3.2 Boundary condition

The velocity inflow boundary condition was employed here. The vertical profiles for U, κ and ε in the atmospheric boundary layer [38] was as follows:

$$U = \frac{u^*}{\kappa}\ln(\frac{z+z_{r0}}{z_{r0}}) \tag{6}$$

$$\kappa = \frac{u^{*2}}{\sqrt{C_\mu}} \tag{7}$$

$$\varepsilon = \frac{u^{*3}}{\kappa(z+z_{r0})} \tag{8}$$

Where z_{r0} is the roughness parameter that was set to 0.01m, κ is the Karman constant (=0.4) and the u^* the atmospheric boundary layer friction velocity. u^* was calculated from a specified velocity at reference height 10m as

$$u^* = \frac{\kappa U_{10}}{\ln(\frac{10+z_{r0}}{z_{r0}})} \tag{9}$$

U_{10} was set to 2.5m/s and 5m/s separately in our study.

The top and sides of the computational domain were given symmetry boundary conditions. All the walls and floor were set as no-slip wall condition. For the outlet of the flow, the convective boundary condition was utilized.

3.3 Calculating method of the single-sided ventilation rate

RNG $\kappa - \varepsilon$ model was employed firstly to reduce time consume, then data of the velocity field after convergence was employed as initial value of LES model. The time step was set to 0.01s according to the reference velocity and cell characteristic [39].

The integration of opening velocities [28] was utilized to calculate the single-sided ventilation rate.

$$Q_{mean} = \frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{N}\left|U_{m,n}\right| \triangle \mathrm{y_m} \triangle \mathrm{z_n} \tag{10}$$

$$Q_{ins,T} = \frac{\frac{1}{2}\sum_{i=1}^{l}(\sum_{m=1}^{M}\sum_{n=1}^{N}\left|U_{m,n}\right|\triangle \mathrm{y_m}\triangle \mathrm{z_n})\triangle t^i}{\sum_{i=1}^{l}\triangle t^i} \tag{11}$$

Where Q_{mean} was utilized to integrate velocities $U_{m,n}$ extracted from a time-averaged flow filed generated by RNG $\kappa - \varepsilon$ model, and $Q_{ins,T}$ was utilized to average the sum of the instantaneous ventilation rates over a time period of $\sum_{i=1}^{l} \Delta\, t^i$.

4 Results and discussion

The following figures and tables illustrate the results obtained from two models and highlight the differences between the two simulations.

4.1 Comparison of steady-state simulation and transient simulation

4.1.1 Characteristic of unsteady wind

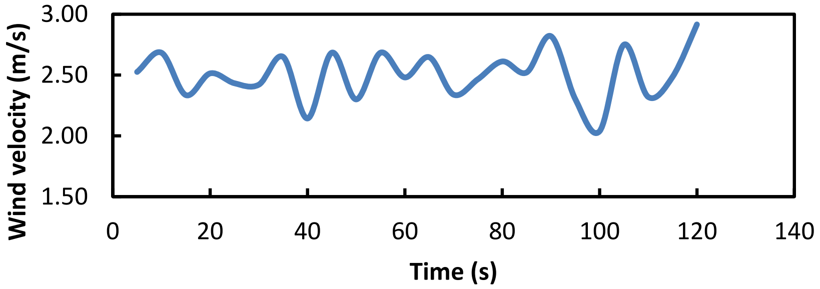


Figure 3 Stream wise component of velocity on the inlet.

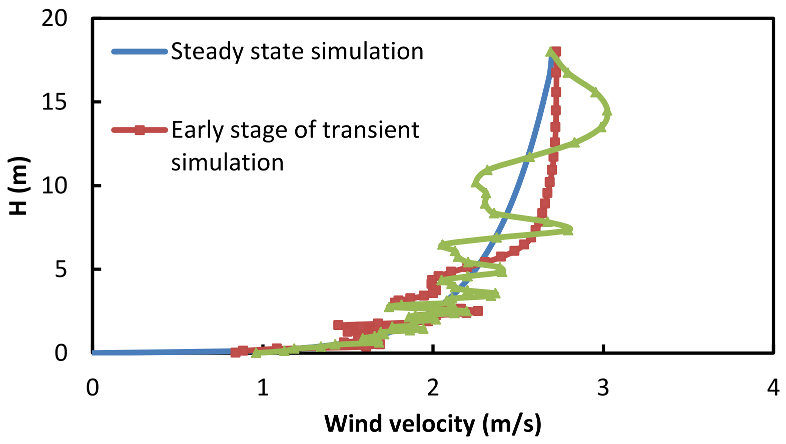


Figure 4 Profiles of Stream wise velocity at the central-line in the inlet surface.

Figure 3 shows the stream wise component of incoming wind on the inlet and with the height of 10m. Different from constant velocity of 2.5 m/s in steady-state simulation, the inlet velocity of transient simulation is time-variant. The root mean square value of fluctuating velocity is about $\sigma_{\bar{U}} = 0.205$m/s. Velocity profiles were taken along the central-line of the inlet surface as shown in Figure 4. The velocities are logarithmic grow with height in steady-state simulation, however, fluctuations occurs in transient simulation. Two velocity profiles of different time were compared in Figure 4. The fluctuation of velocity in lower area decrease but fluctuation of upper part increase over time.

4.1.2 Results of total flow rate of CFD

Table 3. flow rate of the building.

Case	U_{10} (m/s)	Q_{mean} (m^3/s)	$Q_{ins,T}$ (m^3/s)	Q_p (m^3/s)
1	2.5	0.007	0.015	0.005
	5	0.013	0.020	0.013
2	2.5	0.034	0.053	0.001
	5	0.068	0.097	0.005
3	2.5	0.055	0.089	0.015
	5	0.144	0.148	0.044
4	2.5	0.085	0.116	0.018
	5	0.161	0.168	0.052
5	2.5	0.490	0.504	0.007
	5	0.949	1.010	0.037

The calculating results of ventilation rate by numerical simulation were listed in Table 3. It seemed that results of steady state are less than results of transient simulation generally. The similar compared results could be found in Ai's research [28]. Moreover, the steady state results exhibit smaller relative error with large opening area than small opening. The computational cost of LES is at least an order of magnitude higher than that of RANS [27]. Therefore, steady-state simulation can be adopted to analyze single-sided ventilation with large opening if other detailed flow-field information is need but time is limited.

Table 3 also demonstrate that total flow rate increase with opening area and mean wind velocity, as many correlations [40-42] described. Although case 3 and case 4 possess same opening area, their flow rates are distinct. It validate that, as Hu's model indicated, flow rate of single-sided ventilation is related to room volume in a certain degree.

4.2 Pulsating flow rate

The pulsating flow rate calculated by Hu's model was listed in the last column of table3. The pulsating flow rate increases with velocity of wind, and the volume of room respectively. It does not increase with opening area because they cannot meet the condition of exponential growth [16]. For case1, the pulsating flow rate is approximate to CFD results. However, the flow rate calculated by equation (1) is about three times CFD results, and is in relative error by as much as 100%~200%. Opening area ratios of five cases could be divided into 5 groups: 2.08%, 4.16%, 5.56%, 3.13% and 12.50%. Further calculation of related error of pulsating flow rate from Table 3 demonstrated that it basically increase with the porosity. Based on above analysis, 3% was adopted here as a benchmark to discriminate whether the pulsating flow rate can represent the total flow rate.

4.3 Total flow rate

Therefore, the generally model of total flow rate could be predicted by

$$Q = \begin{cases} \sigma_{Qp}\dfrac{\sqrt{2}}{\pi} & (\alpha \ll 3\%) \\ \begin{cases} \bar{Q} & \text{when} \quad \bar{U}/\sigma_u \geq \sqrt{2} \\ \bar{Q} + \left(\frac{2\sqrt{2}}{\pi}\right)\sigma_Q\sqrt{1-\frac{1}{2}\left(\frac{\bar{Q}}{\sigma_Q}\right)^2} & \text{when} \quad \bar{U}/\sigma_u < \sqrt{2} \end{cases} & (\alpha > 3\%) \end{cases} \tag{12}$$

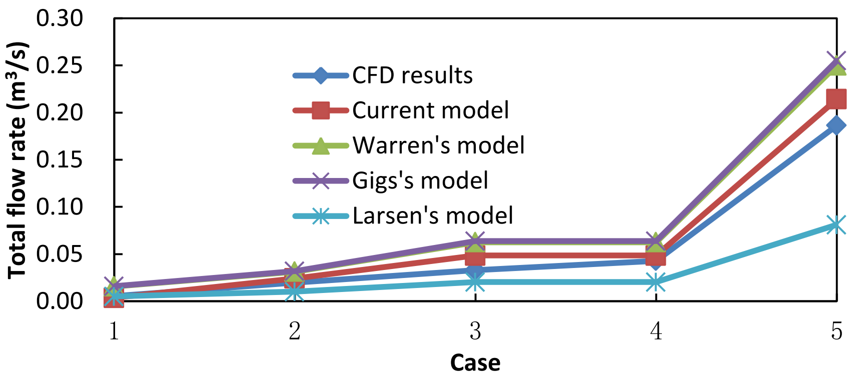
Where α is opening ratio and it represents the ratio of opening area to area of the wall with opening. σ_{Qp} can be calculated out by our pulsating flow rate model. $\bar{Q}$, σ_Q and Q_B can be calculated out by equations (1), (2) and (3).

Results of CFD (transient), current model and other existed models listed in table 4 were compared and analyzed. The temperature of indoor was considered as the same as outdoor in the calculating. Furthermore, mixing coefficient 0.37, was employed to multiply CFD results and current model to get the effective ventilation rate [5].

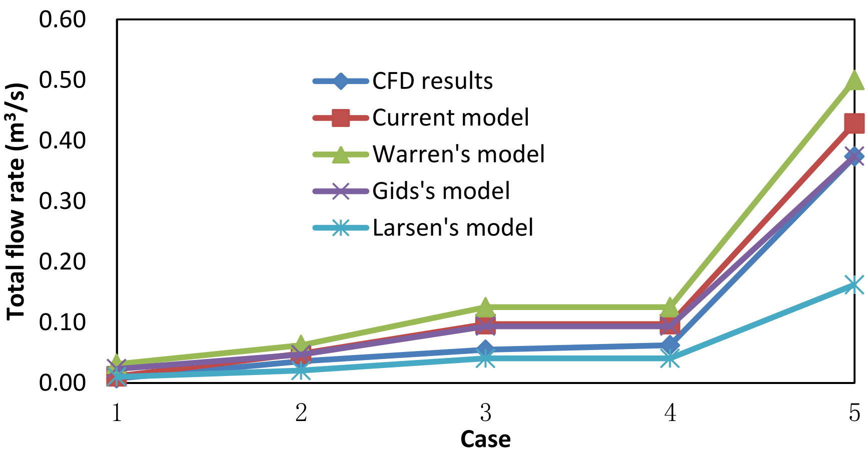
Table 4 Model of flow rate of single-sided natural ventilation

Model	Correlation
Warren[40]	$Q = 0.025AV_R$
De Gids and Phaff[41]	$Q = \frac{1}{2}A\sqrt{c_1V_R^2 + c_2h\lvert\Delta T\rvert + c_3}$
Larsen and Heiselberg[42]	$Q = A \cdot \sqrt{C_1 \cdot f(\beta_W)^2 \cdot \lvert C_P\rvert \cdot V_R^2 + C_2 \cdot \Delta T \cdot h + C_3 \cdot \frac{\Delta C_{P,opening} \cdot \Delta T}{V_R^2}}$

Figure 5(a) shows that Warren's model, Gid's model and current model overestimated the flow rate, the Larsen's model underestimate it on the condition of mean wind velocity 2.5m/s. Warren's model and Gids' model basically resulted in the same flow rate. Figure 5(b) showed the comparing results on the condition of mean wind velocity 5m/s. It is the same as Figure 5(a) that Warren's model, Gid's model and current model overestimated the flow rate, the Larsen's model underestimate it. Our model and Gid's model almost resulted in the same flow rate and all of them were in coincidence with CFD results. Although the result of Gid's model is more approximate to the CFD results in case 5, but current model met the results of CFD well in general.



(a) $\mathrm{U} = 2.5\mathrm{m/s}$



(b) $\mathrm{U} = 5\mathrm{m/s}$

Figure 5 The total flow rate calculated by CFD method, current model and other models.

5 Random mean wind velocity and model simplification

A model for getting total flow rate was verified by above numerical simulation, the inlet velocity was simulated by Fluent among simulation. The wind velocity can also be very easily measured when the field study of natural wind is possible. If not, two-parameter Weibull distribution can be utilized to get the time series of it, then $\sigma_{\bar{U}}$ can be calculated out.

5.1 Random mean wind velocity

The value of mean wind velocity depends on measuring time interval and height which were usually set as 10 minutes and 10m. Constant mean wind velocity come from meteorological stations has traditionally been employed as input parameter under the condition of steady state ventilation, without regarding to the change of it with time. Although the mean wind velocity changes with time, it still has certain statistical regularity. By analysing wind velocity's probability density, it has been found that they are in normal distribution deflecting to left and it conforms to Weibull distribution [43].

The probability density function of mean wind velocity can be described as [43]:

$$p(\bar{U}) = \frac{m}{c}\left(\frac{\bar{U}}{c}\right)^{m-1} \exp\left[-\left(\frac{\bar{U}}{c}\right)^{m}\right] \tag{13}$$

where $p(\bar{U})$ represents probability density of mean wind velocity, m is shape parameter and c is scale parameter. As described in [21], the value of m and c can be estimated by:

$$m = \frac{\ln(\ln T)}{\ln\frac{0.90U_{max}}{\bar{U}}} \tag{14}$$

and

$$c = \frac{\bar{U}}{\Gamma(1+1/m)} \tag{15}$$

where T is observation time, U_{max} is maximum wind velocity for time of T.

On the basis of the above equations, the time series of mean wind velocity can be obtained when average of the mean wind velocity and the maximum wind velocity at the reference height is given. For example, Figure 6 shows the time series of mean wind velocity on condition that mean value is 2.5m/s and the maximum velocity is 8m/s. Figure 7 demonstrates correspondingly probability density of the mean wind velocity. The flow rate changing with time also was shown in Figure 6. The total flow rate could be still calculated by $\bar{Q}$ because of $\bar{U}/\sigma_u \geq \sqrt{2}$.

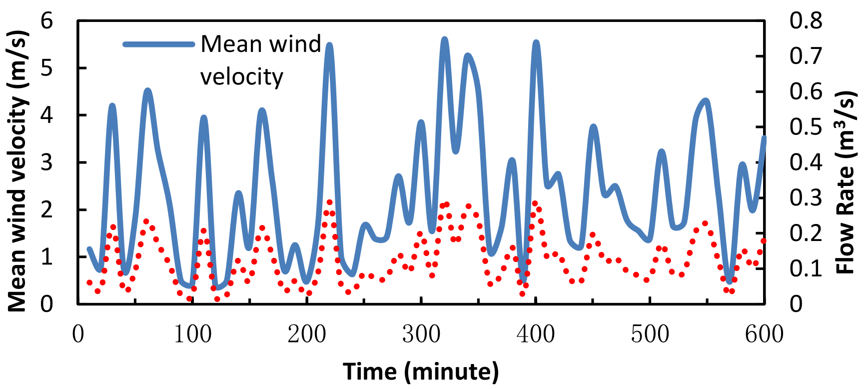


Figure 6 Time series of mean wind velocity and flow rate.

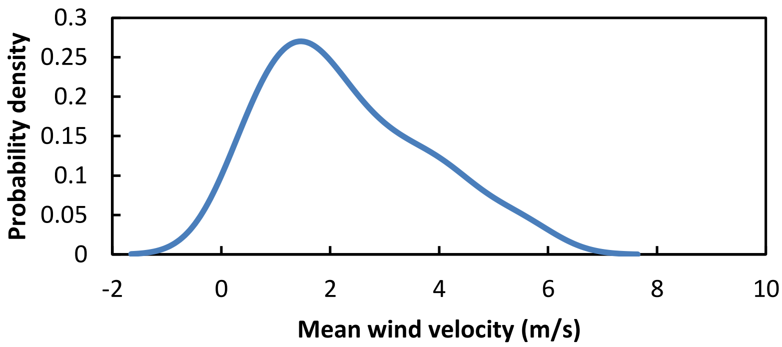


Figure 7 Probability density of mean wind velocity.

5.2 Further simplification of the model

As shown in equations (1) and (2), the vertical position of the neutral plane and corresponding integral value should be calculated out in order to use Chen's model. The following equation can be utilized to get it [2]:

$$\int_{z_0}^{h} \sqrt{z^{2/7} - z_0^{2/7}}\,dz = \int_{0}^{z_0} \sqrt{z_0^{2/7} - z^{2/7}}\,dz \tag{16}$$

To solve it, mathematical tools should be utilized, so it was expected that simple correlation exist. Changing h from 0.5m to 3m, the integral values were calculated out by Matlab. As Figure 9 shows, the integral values grow linearly with opening height basically. Therefore, the integral value can be predicted directly by:

$$\int_{z_0}^{h} \sqrt{z^{2/7} - z_0^{2/7}}\,dz = 0.213h - 0.038 \tag{17}$$

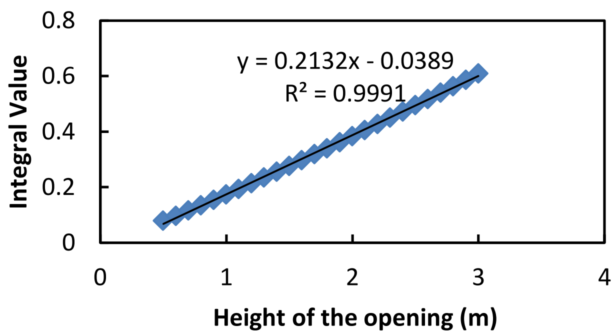


Figure 8. Integral value of different opening height

Therefore, $\bar{Q}$ and σ_Q can be calculated out by：

$$\bar{Q} = C_d \bar{U} l \sqrt{C_p}(0.213h - 0.038)/z_{ref}^{1/7} \tag{18}$$

$$\sigma_Q = C_d \sigma_u l \sqrt{C_p}(0.213h - 0.038)/z_{ref}^{1/7} \tag{19}$$

The value of wind pressure coefficient is related with wind angles of incidence, so above equation can also be applied in other cases that wind is not normal to opening. The value of wind pressure coefficient can be referred to the study of Larsen and Heiselberg [42].

6 Conclusions

Taking into account fluctuating wind velocity driven by the fluctuating pressures and unsteady flows around the opening, this paper proposed a method of predicting total flow rate of single-sided, wind-driven natural ventilation in buildings. Several other correlations and CFD method were utilized to evaluate the performance of the developed model. The study led to the following conclusions:

(1) The total flow rate is majorly caused by pulsating flow when the opening area is small in single-sided natural ventilation. When the opening area is large, the main driving force is pressure difference between upper zone and lower zone of the opening. Then the ventilation rate due to mean airflow is dominant. Opening ratio 3% can be taken as a boundary to distinguish small opening and large opening.

(2) In the case of large opening, mean and broad banded ventilation mechanisms should be counted together when the fluctuation component of mean wind velocity is large. On the contrary, only mean flow rate should be considered with small fluctuation of mean wind velocity.

(3) Generally the mean wind velocity also varies with time. The two-parameter Weibull distribution can be utilized to get the time series of mean wind velocity. Then standard deviation value of fluctuating component of mean wind velocity can be calculated out.

(4) A linear correlation can be utilized to calculate the integral value of mean flow rate. Use of the expression can greatly simplify calculation.

In this study, the ventilation rate due to eddy penetration was ignored. When the incident angle of wind was larger than 70^{o}, the shear layer ventilation should be considered. In addition, the time series of mean wind velocity might be simulated by other precisely method. These should be explored in future studies.

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